

## A THIRD STAR IN THE T TAURI SYSTEM

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### ABSTRACT

New speckle holographic images of the T Tauri infrared companion (T Tauri IRC; T Tauri S) reveal it to be a double system with a sky-projected separation of  $0''.05$ , corresponding to a linear distance of 7 AU. The presence of this third star may account for the relative paucity of dust surrounding the IRC.

*Subject headings:* binaries: visual — circumstellar matter — methods: observational — stars: individual (T Tauri) — stars: pre-main-sequence

### 1. INTRODUCTION

Since its discovery in 1981 (Dyck, Simon, & Zuckerman 1982), the T Tauri infrared companion (T Tauri IRC or T Tauri S) has been the subject of numerous observational and theoretical studies. These have revealed an object with a total luminosity that appears comparable to that of the visible northern star T Tauri N, but which radiates primarily at infrared wavelengths longward of  $2\ \mu\text{m}$ , with a  $V-K$  color  $\geq 12.7$  (Stapelfeldt et al. 1998a). Physical interpretations have ranged from a lower mass (and therefore less evolved and more deeply embedded) pre-main-sequence star (Dyck et al. 1982) to a true protostar (Bertout 1983) or a low-luminosity embedded accretion disk (“mini-FUor”; Ghez et al. 1991). Alternatively, it may be a normal T Tauri star that is coeval with its primary T Tauri N, but that suffers stronger extinction either because of a special viewing geometry with respect to the surrounding diffuse material (e.g., Calvet et al. 1994; van Langevelde et al. 1994) or because it is experiencing an episode of enhanced accretion, perhaps tied to its orbital phase (Koresko, Herbst, & Leinert 1997).

This Letter presents the results of new near-infrared speckle holographic imaging of the T Tauri IRC. The IRC is found to be a close double with an angular separation of  $0''.05$ , corresponding to a sky-projected linear separation of 7 AU at the 140 pc distance to the Taurus star-forming region. The two objects that make up the IRC are designated T Tauri Sa and T Tauri Sb. They are indistinguishable from point sources at the  $0''.05$  diffraction-limited resolution of the telescope, suggesting that they are probably stars. This would make T Tauri at least a hierarchical triple system. In addition to these three stars, the system contains the radio source T Tauri R (Schwartz et al. 1984) and a possible protostar  $30''$  to the southwest (Weintraub et al. 1999).

### 2. OBSERVATIONS AND RESULTS

The new holography data were taken in the CH4 (2.19–2.34  $\mu\text{m}$  FWHM) filter at the 10 m Keck 1 telescope on 1997 December 15 using the Near-Infrared Camera (NIRC; Matthews & Soifer 1994). The observation and data reduction techniques were similar to those described in Koresko et al. (1999). The NIRC Image Converter (Matthews et al. 1996) produced a magnified pixel spacing of  $0''.02$ , approximately Nyquist sampling the diffraction limit at  $2\ \mu\text{m}$ . The observations consisted of 500 exposures of the visual binary, with integration times of 0.15 s for each frame. This short exposure time partially

“froze” the atmospheric seeing, so that the point-spread function (PSF) consisted of distinguishable speckles. The  $0''.7$  separation of the binary was large enough compared to the typical seeing that the PSFs could be separated fairly cleanly in most of the frames.

Individual frames were calibrated in the standard way by subtracting mean sky frames, dividing by flat-field images, and “fixing” bad pixels. A model was computed for the “bleed” signal which extended along the readout direction, and this was subtracted from the calibrated frame. For each frame, a  $32 \times 32$  pixel subframe centered on the IRC was extracted, and a similar subframe centered on the primary served as a measurement of the instantaneous PSF. In 26 of the frames, the instantaneous seeing was too poor for this procedure to cleanly separate the stars, and these frames were rejected. For the remaining 474 frames, the Fourier power spectrum of the PSF frames and the cross spectrum (i.e., the Fourier transform of the cross-correlation) of the masked frame with the unmasked frame were computed. If the primary star is unresolved, then in principle the ratio of the cross spectrum to the PSF frame’s power spectrum is the Fourier transform of the diffraction-limited image. In practice, it was first necessary to correct for noise-bias terms in both the cross spectrum and the power spectrum.

The cross spectrum and the PSF power were accumulated over the whole series of good frames. An averaged Fourier power spectrum and Fourier phase for the IRC were reconstructed from them, and frequencies along the  $u$ -axis, which were corrupted by a small amount of flux from one star leaking into the subframe containing the other, were “fixed” by setting their values to those of their neighbors off the axis. An image was reconstructed from the fixed power and phase with the use of an apodizing function to suppress high-frequency noise. The apodizing function chosen was the product of a Gaussian and a Hanning function. It produced a final image resolution of 49 mas (FWHM). The Fourier components and the image were then rotated to standard orientation. They are presented in Figure 1.

The power spectrum and phase show the striping patterns characteristic of a binary star in a roughly hexagonal region containing spatial frequencies below the diffraction limit of the hexagonal Keck primary mirror. Models were fit to the Fourier components in order to derive the brightness ratio, separation, and position angle of the IRC binary. The fitting was done separately for the power and phase. The quality of a fit was estimated by visual inspection of a display of the ratio of the

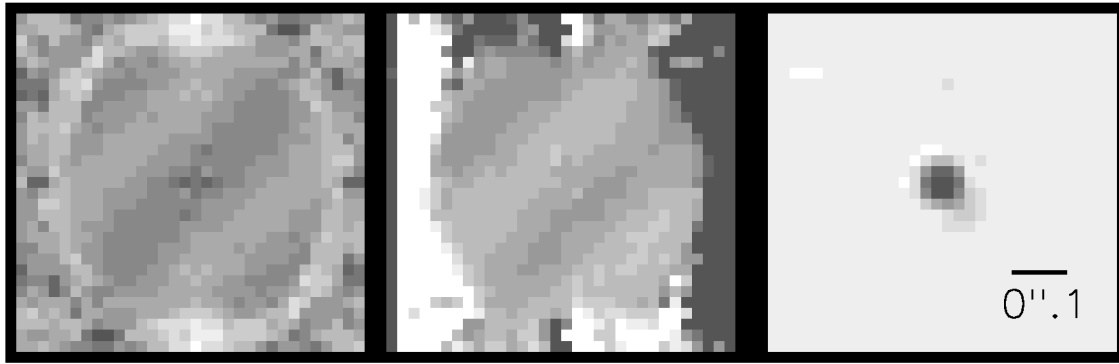


FIG. 1.—Speckle holographic power spectrum, phase, and image of the T Tauri IRC. They have been rotated to standard orientation, with north up and east left. The power and phase show the striping pattern characteristic of a binary star. The zero-frequency point is in the center of the  $(u, v)$ -plane, and the data are bounded in a roughly hexagonal region defined by the diffraction limit of the telescope. For presentation purposes, a constant slope has been subtracted from the phase; this corresponds to shifting the position of the image by a fraction of a pixel. The field of the image is  $0''.64$ . A nonlinear intensity stretch has been applied to the image to make the faint object T Tauri Sb visible.

measured power to the model power and of the difference between the measured phase and the model phase. Limiting parameter values were those for which the binary star striping patterns began to be apparent. The estimates resulting from the power and phase fits are consistent with each other and have comparable uncertainties. The fainter companion, designated T Tauri Sb, is found to lie  $53 \pm 9$  mas ( $\sim 7$  AU) from its neighbor T Tauri Sa along a position angle of  $225^\circ \pm 8^\circ$  and to have only  $0.09 \pm 0.02$  times its brightness. The total flux in the IRC was found to be 0.32 times that from T Tauri N. If the  $K$ -band ( $2.2 \mu\text{m}$ ) magnitude of the system taken as a whole is 5.4 (Rydgren, Schmelz, & Vrba 1982), then applying the brightness ratios measured in the CH4 filter implies  $K$ -band magnitudes of 5.7, 7.0, and 9.6 for T Tauri N, T Tauri Sa, and T Tauri Sb, respectively.

### 3. DISCUSSION

There are two reasons to believe that the double structure seen in the IRC represents a pair of stars and not, e.g., the two bright scattering lobes at the poles of a circumstellar disk seen nearly edge-on (e.g., Koresko 1998; Wood et al. 1998). The first is that they are compact enough to appear pointlike at the  $0''.05$  resolution of the holographic data. The second is that the position angle of the line joining them differs by  $\sim 45^\circ$  from that of the north-south outflow associated with the IRC (Solf & Bohm 1999); if the IRC were a single star surrounded by a disk, one would expect the disk's polar axis to be parallel to the jet.

The presence of a second stellar component in the IRC suggests a simple explanation for the small disk mass implied by the nondetection of the IRC in the submillimeter interferometric measurements made by Hogerheijde et al. (1997) and Akeson, Koerner, & Jensen (1998), which constrain the mass of any disk in the IRC to be no more than  $3 \times 10^{-3} M_\odot$ . A binary companion is expected to truncate a circumstellar disk to a radius  $\sim \frac{1}{3}$  of the binary separation (Lin & Papaloizou 1993; Artymowicz & Lubow 1994), which would suggest a maximum disk radius of only  $\sim 2$  AU in the T Tauri IRC. Although poorly constrained by observations, most disk models assume surface density profiles which place the majority of the mass at larger radii (e.g., Beckwith et al. 1990).

It is clear that both of the stars in the IRC suffer very strong extinction. Visible light imaging using the *Hubble Space Tele-*

*scope* indicates that the IRC as a whole has  $V > 19.6$  (Stapel-feldt et al. 1998a). Even assigning this  $V$ -band magnitude to T Tauri Sb would give it a  $V-K$  color of 10 mag, making it much redder than any stellar photosphere, and any other assumption about the origin of the visible light would require the bluer of the two IRC stars to be redder still. An extinction of  $A_V \sim 35$  would be required to redden a normal stellar photosphere to match the near-IR color of the IRC (Koresko et al. 1997).

The origin of the large extinction to the T Tauri IRC has been the subject of much recent speculation. It is not obviously surrounded by an optically thick scattering envelope as is the IRC orbiting Haro 6-10, another T Tauri star in the Taurus cluster (Koresko et al. 1999). One possibility is that the T Tauri IRC lies behind the disk associated with T Tauri N (e.g., van Langevelde et al. 1994). In this picture, the IRC could be intrinsically quite similar to T Tauri N, with its unusual observational properties resulting from its special viewing geometry. As noted by Akeson et al. (1998), although the radius of the T Tauri N disk appears smaller in their submillimeter images than the distance to the IRC, submillimeter imaging cannot rule out the existence of a more diffuse outer disk such as that proposed by Hogerheijde et al. (1997).

However, this simple picture by itself cannot completely account for the strange properties of the IRC. The T Tauri IRC is one of only two known pre-main-sequence sources of non-thermal, circularly polarized radiation at centimeter wavelengths (Phillips, Lonsdale, & Feigelson 1993; Skinner & Brown 1994), the other being the class I protostar IRS 5 in the Corona Australis "Coronet cluster" (Feigelson, Carkner, & Wilking 1998). This observation hints at the action of some unusual energetic process, perhaps driven by accretion, involving strong magnetic fields.

The north-south jet associated with the IRC lies only  $\sim 11^\circ$  from the plane of the sky (Solf & Bohm 1999). This jet, which has apparently been traced over a distance of  $\sim 1.5$  pc in a giant Herbig-Haro flow (Reipurth, Bally, & Devine 1997), provides independent evidence for rapid accretion. Its axis is nearly perpendicular to the jet from T Tauri N, whose axis lies close to the line of sight and has an east-west sky-projected direction. A variable accretion rate in a luminous disk has been proposed to account for a 2 mag brightening seen during the period from 1987 to 1991 (Ghez et al. 1991).

The observations presented here are not sensitive to the IRC's jet, so it is not clear which of the stars in the IRC is responsible for driving it. The orientation of the IRC's jet close to the plane of the sky suggests that the jet source is likely to be surrounded by a disk viewed nearly edge-on. Integration of the density profile of the model disk described by Wood et al. (1998) along a line of sight  $11^\circ$  from the disk plane and extending from the star to a disk cutoff radius of 2 AU shows that the large extinction required for the IRC could easily be produced with reasonable parameter values, even given the small mass implied by the submillimeter maps. In this picture, both of the stars in the IRC would need to be surrounded by nearly edge-on disks to account for the large extinction they suffer.

The example of HK Tauri (Stapelfeldt et al. 1998b; Koresko 1998) suggests the possibility that the observed near-infrared light may emerge via scattering in the diffuse upper regions of such a disk, rather than simply being highly reddened light directly from the stellar photosphere. The maximum vertical thickness of such a disk would need to be small compared to the  $0''.05$  resolution of the holographic observations, which is plausible if the disk has been truncated. In this picture, the shape of the observed spectral energy distribution may not be representative of the true extinction to the star. Changes in a disk that processes stellar photons via a combination of extinction and scattering might explain how the IRC was able to vary in brightness by a nearly wavelength-independent factor of 5 between 1.65 and  $10\ \mu\text{m}$  (Ghez et al. 1991). Detailed radiative-transfer calculations will be needed to test this possibility.

If T Tauri Sa and T Tauri Sb are indeed stars and have masses  $\sim 1\ M_\odot$ , then their small separation will result in an orbital period of only  $\sim 10$  yr, making the orbital motion readily de-

tectable with the holography technique on timescales of a few years or less. Because the speed of the orbit of the IRC's stars around each other should be much larger than the speed of the IRC as a whole around T Tauri N, it may be possible to use T Tauri N as an astrometric reference and thereby derive an estimate for the ratio of the masses of the IRC stars without fully solving for the orbit. A search for orbital motion will be the subject of an upcoming paper.

#### 4. CONCLUSIONS

The nature of the T Tauri IRC remains a mystery despite extensive observational studies by many workers. That it is a binary whose separation is small compared to the fiducial size of a pre-main-sequence disk offers a simple explanation for the relatively small dust mass required by recent submillimeter observations. But the fundamental question of its evolutionary status remains unanswered: Is the IRC a "normal" young star coeval with the optically visible T Tauri N and simply observed under special circumstances, or a more exotic object with a different evolutionary status?

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